Model of human rhythmic activities on structures*

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Abstract— **Crowd induced dynamic loading in large structures, such as gymnasiums or stadiums, is usually modelled as a series of harmonic loads which are defined in terms of their Fourier coefficients. Different values of these Fourier coefficients that were obtained from full scale measurements can be found in codes. Recently, an alternative has been proposed, based on random generation of load time histories that take into account phase lags among individuals inside the crowd.**

Generally the testing is performed on platforms or structures that can be considered rigid because their natural frequencies are higher than the excitation frequencies associated with crowd loading. In this paper we shall present the testing done on a structure designed to be a gymnasium, which has natural frequencies within that range. In this test the gym slab was instrumented with acceleration sensors and different people jumped on a force plate installed on the floor. Test results have been compared with predictions based on the two abovementioned load modelling alternatives and a new methodology for modelling jumping loads has been proposed in order to reduce the difference between experimental and numerical results at high frequency range.

I. Introduction

The interest in modelling human induced loads has been recurrent since the first accidents on suspension bridges in the nineteenth century like Broughton (1831) in the U.K. or Angers (1850) in France. Accidents and the use of new materials allowing the design of slender structures, the simultaneous interest in the structural serviceability performance such as the one that occurred during the opening ceremony of the London Millenium Footbridge (10 June 2000) made it mandatory to carry out an in-depth analysis of the equivalent actions to be used in the design of structures.

In the last years, interesting contributions are due to Ellis and Ji [1] and Sim [2], but also European research projects [3, 4]. The publication of SCI Guide P354 [5], which incorporates new results such as the Fourier coefficients representing the crowd activities (point 3.1.3) is one of the starting points of the research contained in this paper.

An alternative has been proposed by Sim [6] who has worked on the statistical characterization of phase lag among individuals inside a crowd, based on test results. Thus, the load depends on random factors and is no longer the addition of pure harmonic loads.

In this paper we present a series of tests done on a structure designed to be a gymnasium. Test results will be compared with predictions based on the two abovementioned load modelling alternatives and a new methodology for modelling jumping loads proposed due to the coherence lack between experimental data at high frequency range.

II. Test structure

The test we shall present was performed on a stand-alone building, designed to be a gymnasium, which belongs to the School of Industrial Engineering of the Technical University of Madrid. The structure was finished in the 1950's and, unfortunately, the original as-built drawings are not available.

The photograph displayed in figure 1 shows a general view of the structure, which is neither regular nor symmetric. Many structural details are responsible for that. For example, a large window or an access stair that seems to constrain horizontal displacements at the second bay.

Interior walls are set to split the building in two parts. The big windows on the left belong to the gym, while the small windows on the right, just above the access stairs, belong to the dressing rooms, toilets and other small rooms distributed in two floors. Tests and measurements where only performed on the left hand side.

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Figure 1. External photograph of the structure

III. TEST LAYOUT AND MEASUREMENT EQUIPMENT

Two series of dynamic tests were performed on the gym slab. In the first one, an electro-dynamic shaker was placed at different locations while accelerations and displacements were recorded at selected points of the structure (Figure 2a). In the second one, groups of people placed at inside a reduced area bounced and jumped guided by a metronome. In the latter tests, different combinations of crowd number and metronome frequency were considered (Figure 2b).

Figure 2. Two photographs taken while performing the tests

The electrodynamic shaker APS 113HF is used together with an amplifier APS 145 and a signal generator Hameg HM 8150 that provides the suitable commands. The latter are harmonic signals displaying variable frequencies (chirp), in the range of interest (between 1 and 40 Hz), 100 s long. The whole excitation pattern has been applied in 4 layouts. Figure 3 displays a scheme of one of them, where all sensors are also depicted. The shaker is placed in the second bay of the structure. The other tests were performed with the shaker placed in the middle of the other three bays.

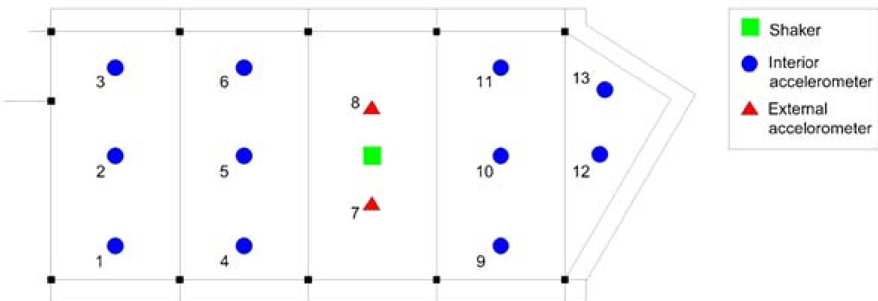

Figure 3. Shaker test layout. Second configuration

A PCB 288D01 sensor was placed at the shaking mass, while 13 other accelerometers (six Endevco 7754-1000 and seven PCB 393A03, see Figure 3) where distributed along the slab measuring along the vertical direction. In the 3 other layouts the shaker replaces the sensors placed at the middle of each bay.

In the second series of tests, a 4 x 3 = 12 m^2 area was drawn centered in the second bay. There, different groups of people were guided in a synchronized motion. Sensor layout was the same as the one in the first series of tests. It should be pointed out that the two sensors inside the jumping area are placed below the slab, outside the gym, in order to disable any interference with the jumpers.

Combining these groups, tests with different numbers of people were carried out: 6, 12, 18, 24 and 30 people, i.e.: densities between 0.5 and 2.5 people/m^2. All jumpers were weighed before starting the tests in order to assess the total load in each set of jumps. The participants had to jump as indicated by a metronome at three main frequencies (1.5, 2 y 2.5 Hz). Figure 4 and Table I illustrates an example of a couple of these group combinations. The grey rectangle is the jumping area.

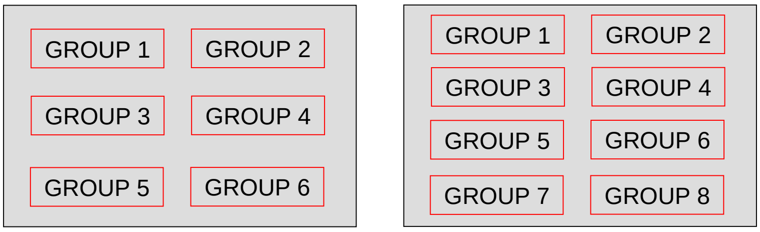

Figure 4. a) Combination 1: 18 people. b) Combination 2: 24 people.

TABLE I. COMBINATION WEIGHTS

	Group							
	1	2	3	4	5	6	7	8
Weight (Kg)	218	213	183	215	242	228	231	224
Total weight (Kg)	1299 (Combination 1)						455	
	1754 (Combination 2)							

IV. STRUCTURAL FE MODEL

A finite element (FE) model of the whole building has been set using ANSYS. Figure 5 displays different views of it. The plots on the left display the structure without walls in order to allow the visualizing all the structural components: the structural columns, and the beams supporting the slab and bound the bays. The roof slab is structurally similar to the floor one.

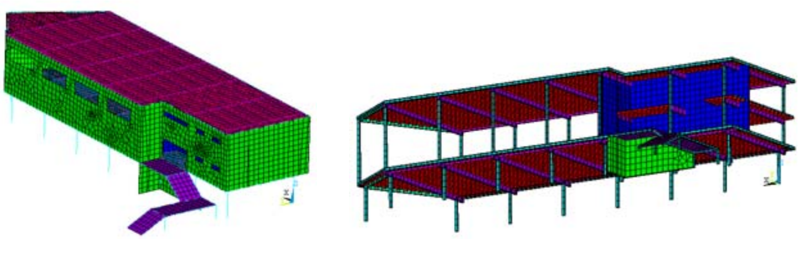

Figure 5. Views of the finite element model

The model has been tuned based on test results: vibration frequencies and frequency response functions among the shaker sensor and those on the slab. Flexural vibration modes associated with vertical motions of both slabs are presented in Table II for both the model and the identification through SSI. Relative errors are below 4% in all cases.

TABLE II. FLEXURAL EIGEN FREQUENCIES COMPARISON

Mode	*Experimental Freq. (Hz)*	*Numerical Freq. (Hz)*	*Error (%)*
1st Floor Bending	5.74	5.71	0.6
2st Floor Bending	6.75	6.59	2.3
3st Floor Bending	8.52	8.20	3.8
4st Floor Bending	10.85	10.89	0.4

V. DYNAMIC LOADING AND RESULTS

The loading induced by the crowd has been modeled considering two existing alternative methodology. The first one may be found in SCI P354 guide [5], where the acting load follows the procedure explained by Ellis [1]:

$$F(t) = W\left\{1+\sum_{j=1}^{3}\alpha_j \sin(\omega_j\, t + j_j)\right\} \tag{1}$$

where W is the weight of the jumpers, ω_j is j times the jumping frequency, ϕj is the phase lag of the jth term and α_j is the Fourier coefficient (or dynamic load factor) of the jth term. α_j and ϕ_j values of the jth term are shown in Table 2 (p is the number or participants)

TABLE III. α_J AND ϕ_J VALUES OF THE J_{TH} TERM

j	α_j	ϕ_j
1	$1.61p^{-0.082}$	$\pi/6$
2	$0.94p^{-0.24}$	$-\pi/6$
3	$0.44p^{-0.31}$	$-\pi/2$

The second methodology is based on the works of Sim [6], which considers randomness in the phase lag among individuals in the crowd. The load contribution associated with the ith jump of each individual has the following form:

$$F(t) = W\, k_{p,\,i} \cos^2\left(\frac{\pi\,(t\text{-}t_{eff,\,i})}{t_{p,\,i}}\right); \qquad \text{for} \quad \frac{-t_{p,\,i}}{2} \le (t\text{-}t_{eff,\,i}) \le \frac{t_{p,\,i}}{2} \tag{2}$$

where W is the weight of the jumper, $k_{p,i}$ is the impact factor, $t_{p,i}$ is the contact period and $t_{eff,i}$ is the effective time. Those three parameters [$k_{p,i}$; $t_{p,i}$; $t_{eff,i}$] are set for each individual and each jump with a statistical model proposed by Sim [6], which is dependent on the main jumping frequency.

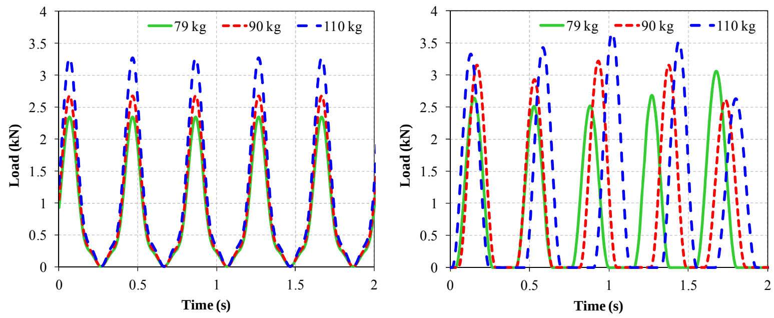

Figure 6. Dynamic loads of three jumpers at 2.5 Hz beat frequency: SCI P354 guide (left) and Sim et al. model (right)

Figure 6a) is consistent with a main jumping frequency of 2.5 Hz, and Fourier coefficients associated with a group of 12 people. Figure 6b) has been built under the same assumptions, but with the second methodology. The time lags and contact duration differences result in a much different pattern.

The loadings are applied to the FE model at selected nodes of the jumping area, one per individual. In each case attention has been paid to identifying the jumper weight at each position during the test. With these loads, a transient analysis is performed by applying modal superposition. The sub-steps are 5 ms long.

Figure 7 displays a comparison of acceleration time histories obtained applying both loadings at the same sensor location (number 8), together with a portion of the one recorded during the test. In this test there were 30 jumpers and the main jumping frequency was set to 2 Hz. As expected, predictions based on SCI P354 become periodic after a few seconds, while Sim's load model leads to a variable pattern, which is closer to the experimental record. It is also interesting to point out that neither load model is able to reproduce the highest amplitude spikes in the experimental record, since the latter are associated to high frequency pulses acting during very short time intervals.

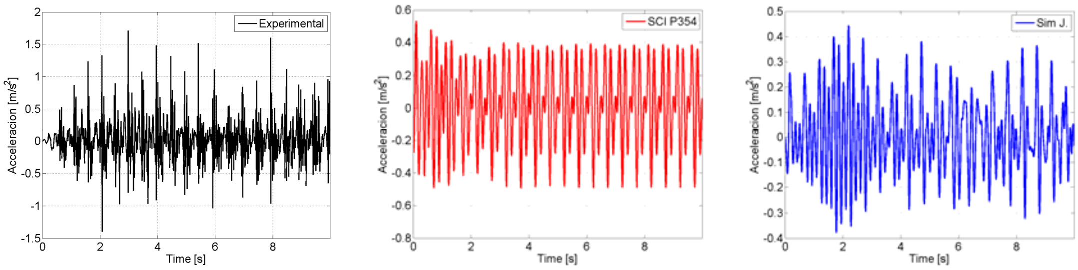

Figure 7. Comparison of acceleration time histories (30 people – 2 Hz)

Figure 8 presents alternative comparisons. Figure 8a) displays the root mean square (RMS) acceleration of the records displayed in figure 5. They have been obtained considering a square window 1s long. All records display an almost uniform pattern around 110 dB, with average differences below 5 dB.

Figure 8b) displays spectral densities. The agreement between predictions and experimental values is remarkable at the jumping frequency and its harmonics (2.5, 5 and 7.5 Hz).

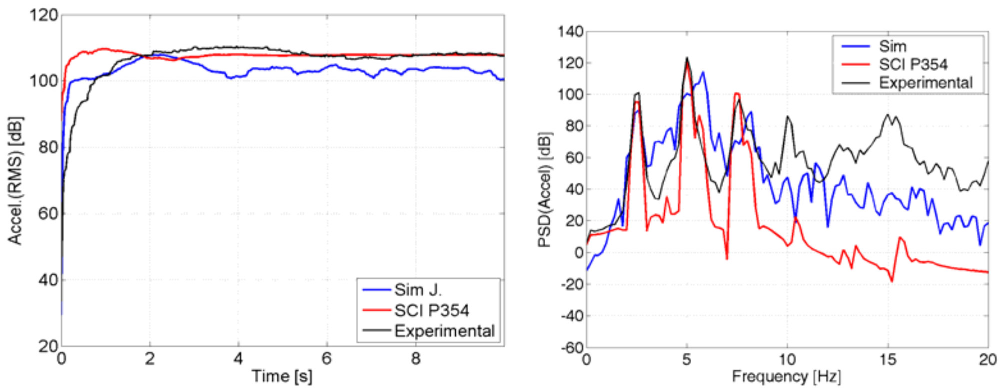

Figure 8. Comparison of running RMS and PSD results (30 people-2.5 Hz)

Randomness in Sim's model translates into a spread of energy across a wider frequency range, which leads to a better fit below 10 Hz. Above this limit, both models underestimate the response. Figure 8b) shows an interesting improvement of predictions using Sim's model in the ranges of frequencies between harmonics of the jumping frequency. However, when natural vibration frequencies are close to the harmonic frequencies associated to jumpers, sometimes, not always, the spread leads to a poorer fit. This feature is very dependent on the degree of synchronization of jumpers during the tests.

VI. PROPOSED LOAD MODEL

From figure 6, it is evident that the SCI and Sim Jump Force Models do not adequately predict the energy contained at high frequencies within the jump force profile. Therefore, the profile would need to be altered in order to more accurately predict the response of the structure.

In order to analyze the jump force profile with more clarity, jump force trials were conducted. A non commercial force plate has been designed for this purpose. The force plate consists of four HBM Model HLCB1C3 load cells, rated at 220 kg each, mounted in a rectangular orientation to support a thick rectangular aluminum plate (Figure 9).

Figure 9. Force plate

The electro-dynamic shaker was used to check the correct operation of the force plate with satisfactory results. Figure 10 shows a photograph of the test, two force time histories and two PSD graphics measured with the force plate and with an accelerometer installed on the moving mass of the shaker.

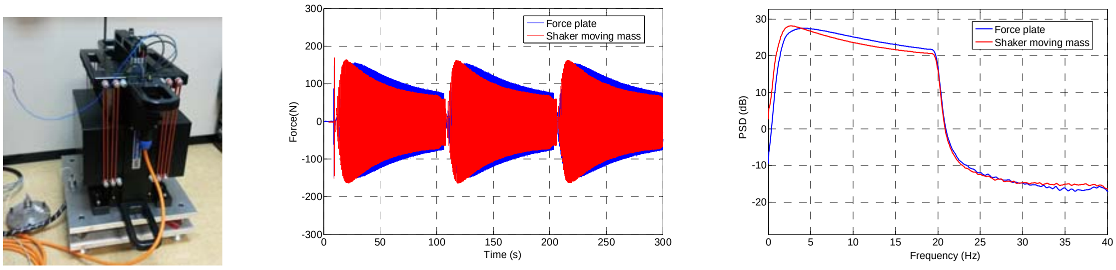

Figure 10. Force plate check tests

Subjects performed sets of jumps at frequencies that included 1.5, 2, 2.5, 2.8, and 3 Hz. The force plate on which the subjects performed the jumps recorded the temporal force profile of the impact. An image of these trials and an example of the temporal responses are depicted in figure 11.

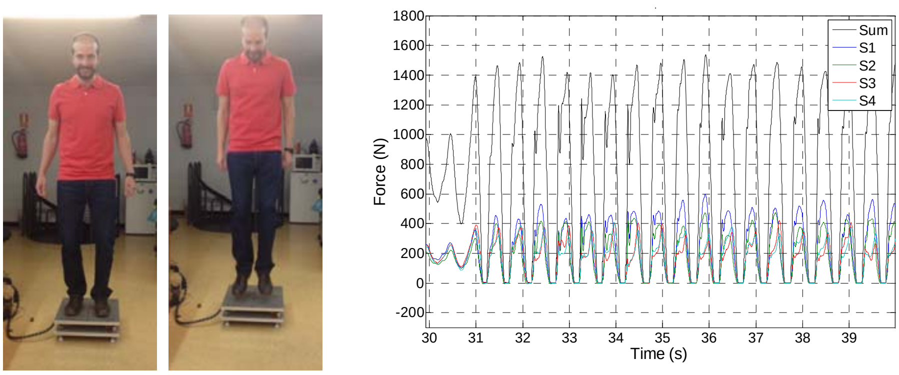

Figure 11. Force plate jump trials and an example of the temporal force history produced

The results of the force plate trials were analyzed in an attempt to better characterize the profile of the jump force and determine how best to approximate it. As shown in figure 11, the jump force can be decomposed into the summation of 1 peak with a large period and a number of peaks with smaller periods. Utilizing a similar model to that of the Sim Model, the approximation will still be comprised of the summation of two square cosines functions. Hence, the same equation will be used as a model.

$$F(t) = A_1 \cos^2(\omega_1(t - t_1)) + A_2 \cos^2(\omega_2(t - t_2)) \tag{3}$$

The idea moving forward was to find average values for the parameters of A1, A2, ω1, ω2, t1, and t2.

In order to do so, an attempt was made to minimize the error between the experimental results of the force plate trials and the approximation function with respect to each individual parameter by an iterative least-squares procedure.

Initially, each jump force profile is isolated from the history of the force plate trial as depicted in figure 12 and figure 13 shows a side by side comparison of the experimental force profiles and the numerical approximations.

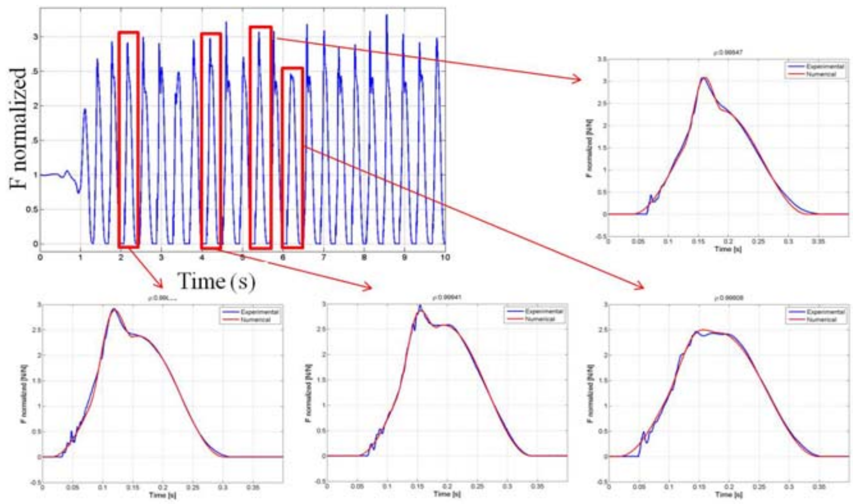

Figure 12. Examples of the process of isolating each jumpo force profile

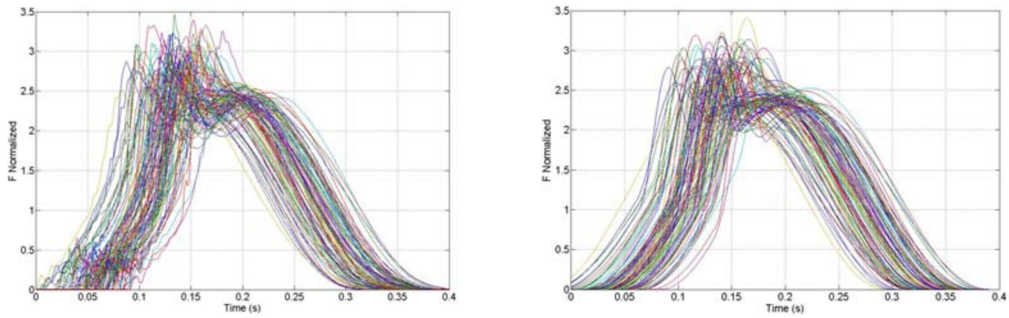

Figure 13. comparison of a) the array of experimental jump force profiles and b) the array of approximations for the jump

For each jump profile in the collection, the total impulse for the experimental and approximate force profiles was calculated. The graph of these impulses is shown in figure 14

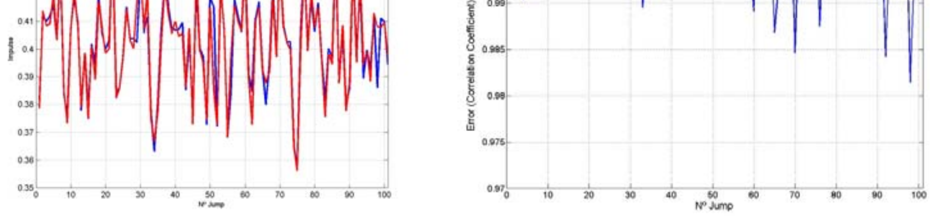

Figure 14. . The correlation coefficients between the experimental jump force profile and the numerical approximation of the jump force profile

As can be seen in Figure 14a), the error between the approximations and the experimental results rarely approaches 1%. In addition, the correlation coefficients between the experimental and numerical force profiles were calculated for each jump, (Figure 14b) and those jumps where the correlation coefficient was less than 0.993 were removed from any subsequent analyses. The correlation coefficients were calculated as follows.

The next step in the process was to obtain a representative statistical distribution for each variable utilized in the approximation. In order to do so, the histograms of the final values for each variable were plotted. Figure 15 displays these histograms as well as the parameters for the normal curves that were fitted to each of the variables.

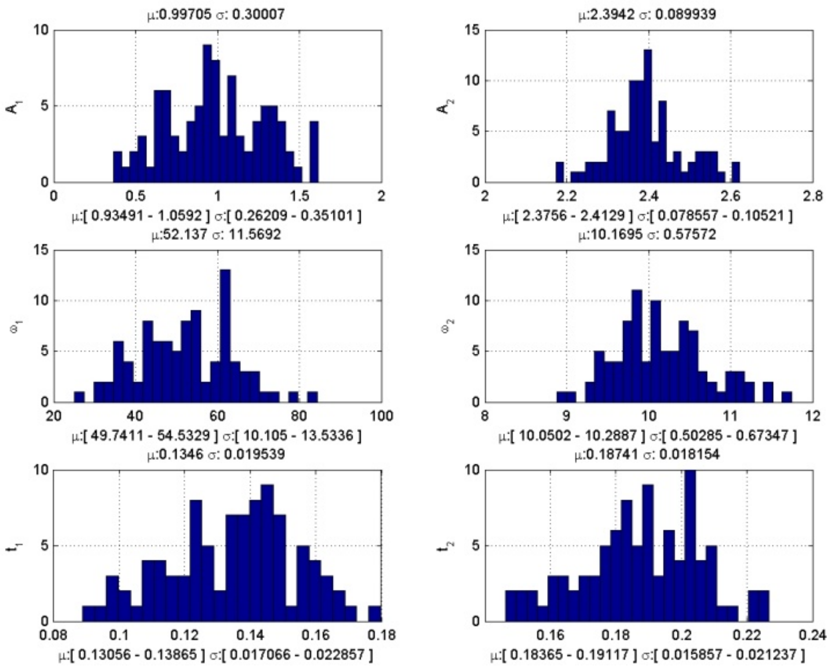

Figure 15. Histograms of variable magnitudes for the jump force approximations

As before, the model for the jump force profiles were programmed so as to simulate the jump forces from the trials conducted within the gymnasium. The resulting simulations of the force histories were used with the finite element model to obtain the structural response to the simulated profiles generated by this new technique. The resulting simulated PSDs were compared with both the experimental results and the PSDs from the jump simulations using the Sim Model. The results are displayed below in Figure 16.

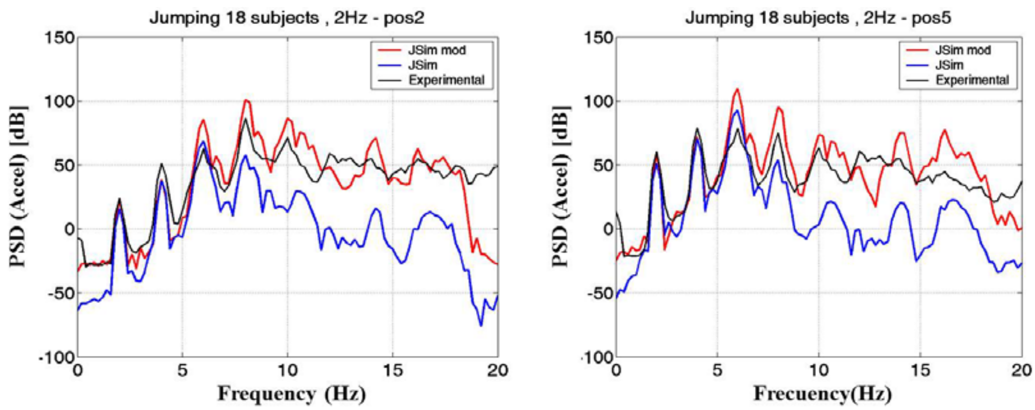

Figure 16. Comparisons of the PSDs produced from the new model, Sim model, and the experimental results for 18 subjects jumping at 2 Hz for two sensor positions

VII. CONCLUSIONS

The main goal of this paper is to assess three different human induced vibration load models (jumps). To this end a series of tests have been conducted on a real structure designed to be a gymnasium, which has natural frequencies within the range of the excitation. Groups of people jumped synchronously guided by a metronome. Also a Finite Element model has been built and fitted considering the vibration modes and frequencies identified using SSI method.

Load models have been found able to reproduce with good accuracy average acceleration levels in the time domain (RMS). However, in the frequency domain, Sim's model is less prone to underestimating response close to structural vibration modes. When compared with SCI's load model, randomness in time lags and contact time durations result on a spread of energy across a wider frequency range, which is closer to actual recorded values.

In regards to the Sim Model, the proposed model provides a clear improvement in the energy contained within higher frequencies of the PSD diagrams. This can be seen clearly in PSDs presented in figure 16. In addition, the proposed model is able to portray the energy contained within the first 4 harmonics of the jump frequencies with a high degree of accuracy.

Another clear advantage of this new modeling technique in regards to the Sim and Modified Sim Models is in the ease of programming and obtaining temporal jump force simulations. The previous models utilized a program where each jump was dependent upon the previous jump and in doing so, a more complex program is required. However, the programming of the new model is accomplished through inputting the statistics for the normal distributions of the variables as well as the correlation coefficients.

Other important point of this work is the design and construction of a force plate in order to develop this new methodology.

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REFERENCES

[1] Ellis B.R. and Ji T., Loads generated by jumping crowds; numerical modeling, The structural Engineer 82 (17), 35-40, 2004

[2] Sim J.H.H., Human-structure interaction in cantilever grandstands, Ph.D. Thesis. University of Oxford, 2006.

[3] Sedlacek G., Heinemeyer C., Butz C., Volling B., RWTH, Aachen; Waarts P., Van Duin F., TNO Institute of Technology; Hicks S., Devine P., The Steel Construction Institute; T. Demarco Profilarbed. Generalisation of criteria for floor vibrations for industrial, office, residential and public building and gymnastic halls, EUR 21972 EN-2006.

[4] Feldmann M. et al, Design of floor structures for human induced vibrations, Joint report prepared under the JRC-ECCS cooperation Agreement for the evolution of Eurocode 3. EUR 24084 EN-2009.

[5] Steel Construction Institute, Design of floors for vibration: A New Approach. SCI P 354. 2007.

[6] Sim J., Blakeborough A., Williams M.S. and Parkhouse G., "Statistical Model of Crowd Jumping Loads, ASCE Journal of Structural Engineering 134(12), 1852-1861. 2008.